# PHYSICAL NOTES ON METEOR CRATER, ARIZONA.

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1. Meteor Crater is situated near the center of the northern half of Arizona, six miles south of the line of the Santa Fe Road, about thirty miles east of Flagstaff. It is an immense hole or crater-like excavation in the otherwise level plain, nearly circular in shape, about 4,000 ft. across at the top, and surrounded by a rim of elevated strata and ejected material. This rim is from 120 ft. to 150 ft. high, and the floor of the crater is 570 ft. below its edge. From the edge there slopes down a very steep inclined talus, ending in the level floor.

The ejected material is mostly composed of broken and irregular limestone boulders from the higher stratum, some sandstone boulders from the next stratum, and an immense quantity of sandstone, which has been pulverized so that each grain of it has been broken into fragments so small that most of them will pass through a 200-mesh. The borings that have been made by the Standard Iron Company have shown that the interior of the crater is filled to a depth of 600 ft. or more with similar fragments of rock and with this pulverized sandstone.

The crater is the center of the area in which the Canyon Diablo meteorites have been found. These are of iron, carrying about 6 to 8 per cent. of nickel, and about three quarters of an ounce of platinum and iridium to the ton. They also contain microscopic diamonds, in large numbers, so that it is a work of great labor and difficulty to cut out a specimen for testing. Another variety of iron is also present, and judging from the residue of iron oxide which it has left, was originally present in much larger quantities than the Canyon Diablo iron. This differs from the Canyon Diablo iron in containing chlorine. It generally is found in oval or globular masses. It oxidizes readily, and forms sheets or plates of iron oxide, resembling fragments of shale, so that it has been called by Mr. D. M. Barringer and Mr. B. C. Tilghman, who first recognized its meteoric origin, shale ball iron.

Through the kindness of the Standard Iron Company the author was given an opportunity to visit and study Meteor Crater. In this paper he desires to present the results of some of his observations, which have to do with physical problems presented by the crater. The description of the crater from the more general point of view, as a geological or cosmical phenomenon, has been given by Dr. G. K. Gilbert, of the U. S. Geological Survey, and by others. The demonstration that it owes its origin to the impact of a meteorite or group of meteorites was made by Mr. Barringer and Mr. Tilghman in papers presented to the Academy of Natural Sciences of Philadelphia, December, 1905, and with additional evidence by Mr. Barringer in a paper presented to the National Academy of Sciences, November, 1909. Professor H. L. Fairchild, of Rochester, and Mr. George P. Merrill, of the U. S. National Museum, have also studied the crater from this point of view.

2. *Magnetism.*—A cylinder 9 cm. long, 1.8 cm. in diameter was cut out of a Canyon Diablo iron, and tested for its magnetic permeability with a permeameter. The method is rough and unsatisfactory, but the only one which can be employed without either wasting too much work on shaping the specimen or possibly altering its condition by heating and working it. The values of $H$, the strength of field, and of $\mu$, the magnetic permeability, are given in the following table, taken from the curve which best represents the observations.

| $H$. | $\mu$. | $H$. | $\mu$. |
|---|---|---|---|
| 4 | 400 | 12 | 530 |
| 6 | 455 | 14 | 505 |
| 8 | 500 | 16 | 472 |
| 10 | 533 | 18 | 442 |
| 10.5 | 540 | 20 | 405 |

Tests with a similar cylinder of Norway iron gave values for $\mu$ about double these, so far as the observations could be carried.

The pieces of shale ball iron at the author's disposal could not be prepared for the test with the permeameter. All that could be done with them was to examine their behavior in the earth's magnetic field by the aid of a small magnet. They generally behaved like pieces of soft iron, or like pieces of the Canyon Diablo iron of about the same size.

A shale ball perhaps 9 in. in diameter, and which was entirely oxidized, was examined in position, soon after its discovery. It was found by excavating in the pulverized sandstone on the outer rim of the crater. It showed strong local poles scattered over its surface. In general, the polarity of the top was south, that of the bottom, north, but at many points the opposite polarity was found.

A piece of shale ball iron about 3 in. in diameter and 1 in. thick, when tested at the crater, showed north polarity all over the outer rim, and south polarity at two nearly opposite points on the two faces. This specimen was sent on to Princeton in a box with other specimens, and when tested again, this peculiar disposition of polarity no longer existed, and it now behaves like soft iron. This fact makes it improbable that the magnetic condition first observed was due to a superficial coating of magnetic oxide, and indicates that it was rather a real magnetic state of the iron. The shale formed from a shale ball by oxidation often shows very peculiar radial structure, and one is tempted to believe that this structure exists in the shale ball iron, and that it may be accompanied by a radial intrinsic magnetization. This view is borne out by some peculiarities of the magnetism of pieces of the shale, but the specimens of shale ball iron found are too few, and have been handled too much since they were found, to make it possible to test this view at present. Much of the shale is so feebly magnetic as hardly to affect a magnetic needle, even when close to it. Occasional pieces are strongly magnetic with well developed poles.

In 1891 Mr. Marcus Baker made a careful magnetic survey within the crater, and along lines running out on the plain. He found no evidence of any local magnetic field. The author ran some straight lines across the floor of the crater with a sensitive surveyor's compass, which could be read by estimation to about 2′ of arc, and found no variation in the compass deviation at different points on these lines. He also made a number of determinations of the magnetic dip, using a Kew Dip Circle. The mean value of the dip found by fifteen observations was 62° 7.7′, with maximum variations at different points from the mean of — 5.1′, and + 4.2′. These variations may have been due to errors of observation, but are probably to some extent real and due to local conditions. There are several drill holes in the floor of the crater in which the iron pipes used in sinking the holes were abandoned, and these pipes could easily modify the general field to such an extent as to account for the different values of the dip which were found.

If the size of the meteor by which the crater was made is estimated by the old rules of artillery practice, we should conclude that it is equivalent to a sphere of about 750 ft. in diameter. A sphere of iron of this size at the appropriate depth below the floor of the crater would seriously affect the magnetic field. Even on the more moderate estimates of Mr. Barringer and Mr. Tilghman that it is equivalent to a sphere 250 ft. in diameter, the values of the dip at the extreme stations, at which the dip was observed, should differ by 30′. That no such difference was found argues that the meteor was broken and scattered by the impact, or more probably, as Mr. Barringer strongly argues in his latest paper, was a cluster or swarm of small masses of iron, mostly of the shale ball variety. The possible intrinsic magnetism of these masses, coupled with the possibility that they have gradually oxidized in the depths of the crater, would account for the absence of any observed magnetic field.

3. *Mechanical Effect of the Impact.*—When the map of the crater, showing the distribution of the ejected material, is studied, a remarkable symmetry of distribution is immediately apparent. A line drawn through the center of the crater, 13° west of north, can be taken as an axis of symmetry. This line on the north rim of the crater passes through or near the lowest part of the rim, and the region where the least ejected material is found. Its other end on the south rim passes through the middle of the greatest bulk of ejected material, which is furthermore found there in small fragments or largely in the form of pulverized sandstone, or "silica." Just to the east of it, where it has been driven by the

prevailing winds, is an area of brown sand, which the borings prove has come from the depths of the crater. The central line at right angles to this axis crosses the rim at or near the middle of two opposite areas on which the ejected material is deposited in large boulders, mostly of limestone, coming from the upper stratum of the formation. In two lines from the center 33° west and 42° east of this axis, toward the south, there lie out on the plain rows of limestone boulders, marked on the map as the furthest thrown limestone boulders.

The map showing the effect of the disturbance on the original strata exhibits this symmetry in another way. Starting where the axis crosses the northern rim, where the strata are inclined at only 5°, and proceeding around the rim in either direction, the strata gradually tilt more and more, reaching an inclination on one side of 50°, on the other of 80°. At about 135° around the rim on either side we find a fault and a short stretch in which the strata stand vertically. These two narrow regions are ended by faults which separate them from the remaining part of the rim, through the middle of which the south end of the axis passes. This portion of the rim is simply lifted about 100 ft. and the inclination of the strata is 0°. The lines of the furthest thrown limestone boulders are nearly over the two regions in which the strata are vertical.

The experiment was tried of shooting a half inch spherical lead ball from a high-power rifle into a level floor of smooth densely packed silica. The inclination of the shot was about 30° from the vertical. The tilting of strata, of course, could not be observed; but the distribution of ejected matter on either side of the plane of incidence was remarkably like that described in the preceding account of the crater. The greatest amount of finely powdered material formed a rim to the shallow hole, ahead of the bullet. The edge over which the bullet passed had little or no matter piled up on it. The edges diametrically opposite, across the line of flight, were lined with powder and many lumps of silica, still forming definite masses, though the material is so friable that it was hard to pick up one of these lumps with the fingers without crushing it to powder. On either side of the plane of incidence, making angles with it of about 40°, were many fine marks or scratches in the smooth floor, showing where small particles had been driven ahead with great violence. The hole had sloping walls and an inner level floor. A sketch map made from the bullet hole and a map of the crater in which only those details are preserved which the bullet hole can show, are remarkably similar.

The theory of the strains which would end in such a distribution of the broken material ejected by an impact cannot be given; but the observations direct attention to some interesting peculiarities. The piling up of most of the ejecta ahead of the projectile is what might be expected, but it is less obvious that the stresses should be so distributed as to break up the material on either side of the line of flight into separate blocks and arrange them on either side of the hole along the rim. The two spurts of small fragments, thrown out forward diagonally from the line of flight, are also remarkable.

The lead bullet used was torn to fragments, and much of it was flung out of the hole. The other bullets tried, of other material, were generally badly deformed and torn; and were thrown backwards out of the hole, either whole or in fragments. The steel bullets were the only ones which retained their shape, and they remained buried in the holes made by them. It does not seem probable that much, if any, of the meteor which made the crater was thrown out of it in a similar way.

4. *Energy.*—The data from which to determine the energy with which the meteor struck the earth are not precise; but an estimate can be made of the energy with some degree of plausibility.

The work done in excavating the crater is insignificant in comparison with that done in crushing the rock. The mass ejected may be estimated at 330 million tons (of 2,000 lbs.). This is considerably more than the mass excavated in the construction of the Panama Canal. The bottom of this mass was 500 ft. below the original surface. To lift the mass up and clear of the hole would probably use $16 \times 10^{10}$ ft. tons. Something more must be added for the work of tilting back the strata and lifting the unbroken rock masses all around the rim to a height of 100 ft. Perhaps $20 \times 10^{10}$ foot tons spent in mechanical lifting would not be an overestimate.

Most of the energy was spent in breaking up the rock, and especially in shattering the grains of sandstone into the very finely pulverized silica. Only a rough guess can be made of the amount of this silica, but large parts of the ejecta consist of little else, and the borings have shown that the crater also contains great quantities of it. From the probable size and shape of the whole cavity it appears that over 500 million tons of rock were broken up. Of these, perhaps one fifth, or 100 million tons, are in the form of pulverized silica. The work done when this silica was formed was expended in separating the particles and in rubbing them over each other. The work done against friction must have been retained as heat. The temperature generally did not rise to the melting temperature of quartz, for the grains of silica rarely show evidence of fusion. A small quantity of melted quartz is found, which is full of blow holes, as if, when melted, the mass had been pervaded with an expansible vapor. One way of explaining this formation is to suppose that it represents the fusion of the shattered quartz in the presence of water, which is known to be present occasionally in pockets in the generally dry sandstone, the superheated steam formed at the same time accounting for the porous state of the material. If this explanation is correct, it indicates that the temperature of much of the silica was nearly that at which quartz melts when dry, and above the temperature at which it melts in the presence of water. If we set, as an outside limit of temperature, 2500° C., and suppose all the silica heated to that extent, the heat developed is equivalent to $9.25 \times 10^{13}$ ft. tons. It is possible to ascribe the melting of the quartz to the heat more directly developed in the neighborhood of the advancing meteor. In this case it is more difficult to fix a lower limit of temperature for the silica. The iron found outside the crater in the silica shows no evidence of melting, and the Widmanstatten figures are preserved. If we assume the general temperature of 625°, to keep it not only below the melting point of iron, but also below that temperature at which the Widmanstatten figures disappear, the heat developed in the silica would then be equivalent to $2.3 \times 10^{13}$ ft. tons.

The work done in the silica is surely only a fraction of the whole. A layer of hard limestone, 300 ft. thick, was also broken up, and much of it must have been pulverized also. After all, we can do no better than guess; but taking all the work done into account we may, in my opinion, estimate it without exaggeration, at $60 \times 10^{12}$ ft. tons.

Such a projectile as would have made the crater would have reached the earth without retardation by the atmosphere. If it were moving, as a comet does, with the parabolic velocity of 25 miles a second, and were to encounter the earth head on, it might fall with a velocity something over 43 miles a second. We may set the outside limits of velocity at 3 and 48 miles a second. With the lowest velocity the mass required to bring in the estimated energy is $15 \times 10^6$ tons; with the highest velocity only 60,000 tons.

The mass of the meteor may otherwise be estimated from the size and shape of the crater. Experiments with cannon shot, quoted by Mr. Tilghman, show that with velocities of 1,800 ft. a second, the depth of the hole made in limestone rock is about twice the diameter of the shot, and its width at the top about five times the diameter. These proportions were well borne out by observations with spherical rifle balls shot into sandstone. If these proportions held for the crater they would indicate a projectile 750 ft. in diameter, with a mass of about $50 \times 10^6$ tons. This is evidently an over-estimate. The mass indicated in this way is however of the same order of magnitude as the greatest mass indicated by the estimates of the energy and velocity. Manifestly the extreme velocities estimated are not probable, so that the mass is probably neither so large nor so small as the extreme values obtained. A mass of 400,000 tons moving with a velocity of from 18 to 20 miles a second would bring in the estimated amount of energy. In the absence of other evidence this seems a reasonable mass to assign to the buried meteor.